NEAR-INSTANTANEOUSLY ADAPTIVE COOPERATIVE UPLINK SCHEMES BASED ON SPACE-TIME BLOCK CODES AND V-BLAST

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***Abstract* - In this paper we propose two adaptive schemes for improving the achievable Bandwidth Efficiency (BE) of cooperative diversity aided wireless networks. These schemes are capable of accommodating the channel signal-to-noise ratio (SNR) variation of wireless systems by near-instantaneously adapting the uplink transmission configuration. Explicitly, the first adaptive transmission scheme is constituted by a novel reconfigurable four-antenna-aided cooperative uplink space-time block coded (STBC) structure designed for communicating with a Base Station (BS) equipped with a single receive antenna. By contrast, the second adaptive scheme is constituted by a reconfigurable cooperative uplink vertical Bell Labs Layered Space Time (V-BLAST)-like architecture constituted by single-antenna-aided mobiles communicating with a BS equipped with multiple receive antennas. Our results demonstrate that significant effective BE improvements can be achieved by both systems, while maintaining a target bit-error-ratio of 10^{-3}. Explicitly, when neglecting the Nyquist excess bandwidth, the first system is capable of attaining an effective BE varying between 0.316 bits/sec/Hz and 2.18 bits/sec/Hz, while the second has a BE varying between 2 bits/sec/Hz and 8 bits/sec/Hz.**

1. INTRODUCTION

The fundamental limitations of reliable wireless transmissions are imposed by the time-varying nature of the typical multipath fading channels, which may be efficiently circumvented by sophisticated transceiver design [1] employing multiple antennas at both the transmitter and the receiver. Recent information theoretic studies [2, 3] have revealed that employing a multiple-input multiple-output (MIMO) system significantly increases the capacity of the system. In [4], Wolniansky $et\ al.$ proposed the popular multi-layer MIMO structure, known as the Vertical Bell Labs Layered Space-Time (V-BLAST) scheme. The V-BLAST receiver is capable of providing a tremendous increase of a specific user's effective bit-rate without the need for any increase in the transmitted power or the system's bandwidth. However, its impediment is that it was not designed for exploiting transmit diversity and the decision errors of a particular antenna's detector propagate to other bits of the multi-antenna symbol, when erroneously cancelling the effects of the sliced bits from the composite signal.

Whilst V-BLAST was designed for maximising the achievable multiplexing gain, Alamouti [5] discovered a witty transmit diversity scheme, referred to as a space-time block code (STBC), which was designed for a high diversity gain. The attractive benefits of Alamouti's design motivated Tarokh $et\ al.$ [6] to generalise Alamouti's scheme to an arbitrary number of transmit antennas. STBC uses low-complexity linear processing at the receiver side for detecting the transmitted signals and is capable of achieving the maximum possible diversity gain.

MIMO systems require more than one transmit antenna, but satisfying this need may be impractical for shirt-pocket-sized wireless devices, which are typically limited in size and hardware complexity to a single transmit antenna. Furthermore, as most wireless systems support multiple users, user cooperation [7–9] can be employed, where users support each other by "sharing their antennas" and thus generate a virtual multi-antenna environment [10]. Since the signals transmitted from different users undergo independent fading, spatial diversity can be achieved through the cooperating partners' antennas.

Adaptive modulation and coding techniques that track the time-varying characteristics of wireless channels can be used for significantly increasing the achievable data rate, reliability and spectral efficiency of wireless communication systems [11]. In recent years various Adaptive Coding and Modulation (ACM) assisted schemes have been proposed [12, 13]. The fundamental goal of near-instantaneous adaptation is to ensure that the "most efficient" mode is used in the face of rapidly-fluctuating time-variant channel conditions based on appropriate activation criteria. As a benefit, near-instantaneously adaptive systems are capable of achieving a higher effective BE compared to their non-adaptive counterparts.

Against this state-of-the-art, in this paper we propose two adaptive systems exploiting the combined advantages of user cooperation, amalgamated with the diversity gain of STBC as well as the multiplexing gain of the V-BLAST architecture. The systems assume the formation of a cluster of four users communicating with a common Base Station (BS). The transmission mode of the four cooperating users is adapted by activating four different modes according to the near-instantaneous channel Signal-to-Noise Ratio (SNR) averaged over the four users. In the first system, the total number of users supported is fixed, while the modulation scheme is adapted. On the other hand, the second system adapts the number of users to be served by activating or deactivating a cooperating user in response to the near-instantaneously fluctuating SNR. In general, the proposed systems transmit using a more error-resilient but low-Bandwidth Efficiency (BE) mode, while encountering a low near-instantaneous SNR and activate a high BE transmission mode, when the near-instantaneous

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SNR is high.

This paper is organised as follows. In Section 2, a brief system overview is presented, followed by a discussion on the architectural philosophy of the proposed adaptive systems in Section 3. In Section 4, we demonstrate how the proposed system performs and finally we conclude in Section 5.

2. SYSTEM OVERVIEW

The system we consider is a cellular system employing user cooperation. Cooperation starts by forming clusters of users, where the users within a cluster cooperate by transmitting data to a common BS, in order to achieve a diversity gain. The specific assignment of users to a given cluster is based on the quality of the Inter-User Channels (IUC), where we assume that the IUC quality is statistically speaking better than the individual uplink quality. This is a reasonably practical assumption, since users within a cluster are located closer to each other than to their serving BS. In this contribution, we focus our attention on characterising the performance of a single established cluster, without being concerned about the protocols used for setting up a cluster. Moreover, for the sake of supporting the exchange of data amongst the cooperating users, we assume a Time Division Duplexing (TDD) system where users share their data amongst each other on different time slots before communicating with the BS. Furthermore, we assume perfect synchronisation between the transmitting users. This assumption becomes reasonably accurate when the distances between the users of a cluster are small compared to the distance separating the users from the BS, provided that the users have been instructed by the BS to advance their transmission instants according to their propagation delays, i.e. distances, so that their signals arrive at the BS quasi-synchronously[1]. Moreover, we consider transmissions over a correlated narrowband Rayleigh fading channel, associated with a normalised Doppler frequency of $f_D = f_d T_s = 0.01$, where f_d is the Doppler frequency and T_s is the symbol duration. The complex Additive White Gaussian Noise (AWGN) that contaminates the received signals is a zero-mean complex Gaussian random variable having a variance of $N_0/2$ per dimension, with $N_0/2$ representing the double-sided noise power spectral density expressed in W/Hz.

We assume a TDD system, where the correlation between the fading envelope of the UpLink (UL) and the DownLink (DL) is high, since the UL and the DL slots are transmitted at the same frequency and at a low TDD time-slot displacement, hence they are likely to fade coincidentally in low-Doppler pedestrian scenarios, unless frequency-selective fading is encountered owing to the high-rate transmissions. Therefore, when transmitting a frame, the BS estimates the SNR of the receivers at the other end of the link based on the SNR estimate at the BS and selects the most appropriate transmission mode accordingly.

3. PROPOSED ADAPTIVE SCHEMES

In this section we propose two adaptive cooperative diversity aided systems. The proposed adaptive systems are designed to serve a cluster of four uplink users communicating with a common BS, where each of the users has a single transmit antenna. Moreover, the proposed System 1 is used when the BS is equipped with a single receiver antenna, whereas when the BS has four receive antennas, the proposed System 2 can be used. A high-level block diagram of the proposed system is shown in Figure 1. It is worth noting that the proposed schemes can be readily generalised to any number of users. We assume that a suitable transmission mode of the four users cooperating within a cluster is selected according to the near-instantaneous channel conditions of the four users, which is quantified in terms of their average SNR.

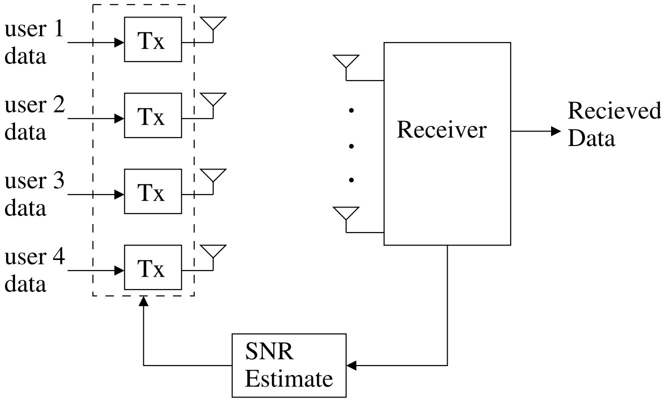

Figure 1: The proposed adaptive system model.

As shown in Figure 1, each user transmits his/her data by activating a specific mode of operation, depending on the near-instantaneous channel conditions. Each user's data is received by the BS as well as by the other users in the cluster, which can be exploited later by the Mobile Stations (MS) for cooperation using the detect-and-forward strategy [7]. At the BS side, the receiver applies the appropriate decoding process according to the specific transmission scheme employed and estimates the near-instantaneous SNR averaged over the users within a cluster to decide on the transmission scheme for the next transmission frame or packet.

The main objective of introducing the proposed systems is to maximise the achievable system BE, while maintaining a specified target BER performance that guarantees a certain quality-of-service level. More specifically, in this treatise we aim for maintaining a target BER of 10^{-3}, while transmitting data at the highest possible effective BE at the near-instantaneous SNR experienced by the transmitted data frame.

The first proposed system, referred to as System 1, attempts to maximise the achievable BE of *each individual user* by varying the modulation scheme used for transmission. Specifically, the four cooperating users form a virtual space-time block coded structure according to G4-like [14] genarator matrix, while varying the modulation scheme used between BPSK in the lowest-BE transmission scheme and 64-QAM in the highest-BE transmission scheme. As it will be detailed explicitly in Section 3.3.2, the G4-like [14] STBC mode is formed by allowing the four users in the cluster to detect-and-forward the data received from their cooperating partners, in order to form a four-antenna STBC structure. In order to be able to use this STBC-like structure, each cooperating user has to share his/her data with the other three cooperating users before transmission without compromising the privacy of the data. In other words, the cooperating users are not allowed to decipher other users' data. Again, the system employs TDD for exchanging the data between the different users. That is, each user is assigned a time slot for broadcasting his/her data to the other cooperating users in the same layer, before communicating with the BS. More explicitly, when the four users implement a virtual four-antenna aided G4-like [14] STBC system, the system needs four Time Slots (TS) for the four users to communicate their data amongst each other for cooperation. Then, the G4-like transmission requires another eight time slots for the uplink transmission. This means that the four users require a total of twelve TSs for the transmission of a single TS of data per user. However, the number of TSs required can be reduced, and hence the BE increased, if we consider the fact that the data exchanged by the four users in the first four time slots

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[1] In the currently operational cellular systems, this procedure takes place during the call-set-up phase and it is then regularly updated using adaptive timing advance control.

is decoded by the BS and this means that the first row in the G4-like transmission matrix is no longer required, i.e. the four cooperating users do not transmit their data again to the BS, since it was already received by the BS while the users were sharing their data amongst each other. In other words, we take into account that the first row in the G4 matrix is also simultaneously received by the BS, while the users are exchanging their data amongst each other and this saves the exclusive allocation of a TS from the above-mentioned total of 12 TSs assigned to cooperative transmission. In summary, the transmit diversity gain of the cooperative STBC is achieved at the cost of using more TSs and hence reducing the achievable effective BE.

By contrast, the second proposed system, referred to as System 2, attempts to maximise the achievable BE of the *entire cluster of four cooperating users* by adapting their transmission configuration. The system commences its operation in a four-layer V-BLAST-like transmission configuration supporting all of the four users within the cluster. If the near-instantaneous SNR averaged over the four users drops below a certain threshold, the cluster has to be reconfigured in a more robust but lower-BE mode by dropping a user to form a virtual three-layer V-BLAST system, while providing the user just dropped from the cluster with a dedicated channel. If the near-instantaneous SNR averaged over the remaining three users drops further below a certain threshold, the cluster drops another user and the BS provides this user with a dedicated channel for his/her communication. This process is continued, until each user has his/her own dedicated channel in the lowest-BE mode. On the other hand, as the near-instantaneous SNR increases, the system incorporates an additional cooperating user in the cluster. The user added to the cluster is the one who had the highest near-instantaneous UL SNR in his/her dedicated channel. This system does not require any exchange of data between the cooperating users, since the users are cooperating to share the system resources such as the carrier frequency and the bandwidth, rather than for the sake of achieving an additional diversity or multiplexing gain. The system activates and deactivates users in the cluster according to the near-instantaneous received SNR. As the number of users cooperating in a cluster decreases, the level of interference at the receiver side decreases and this results in a better performance. Again, the transmission regime of the cluster is adapted for the sake of maximising the total BE, while maintaining a target BER of 10^{-3}.

3.1. V-BLAST

V-BLAST, as mentioned previously, provides a high BE in exchange for a low diversity gain. Let $\mathbf{x}^T = [x_1 \quad x_2 \quad x_3 \quad x_4]$ denotes the vector of symbols to be transmitted by the four users during a symbol interval. Then the corresponding vector of the received signal can be represented as

$$\mathbf{r}_t = \mathbf{H} \cdot \mathbf{x}_t + \mathbf{n}_t, \tag{1}$$

where $\mathbf{r}_t$ represents the vector of received signal at the BS, $\mathbf{H}$ is an $(n_r \times n_t)$ matrix where n_t is the number of users transmitting simultaneously, n_r is the number of receive antennas at the BS and h_{ij} represents the channel coefficient between user j and the BS antenna i, while $\mathbf{n}_t$ denotes the noise vector at time instance t.

V-BLAST detection is carried out using SIC and the zero forcing (ZF) algorithm [4].

3.2. Four-Antenna STBC

STBC has the potential of achieving the maximum transmit diversity order specified by the number of transmit antennas n_t as well as receive antennas n_r, while using maximum-likelihood decoding based on linear processing of the received signals. Again, in this paper we use the four-antenna based $G4$ STBC scheme of [6, 14] for transmitting the data from the four cooperating users forming a cluster. The $G4$ STBC structure has an effective rate of $R = 1/2$ and a diversity order of $4n_r$.

The $G4$ STBC scheme can be described by the following transmission matrix of [6, 14, p.404], where each column corresponds to the data transmitted by each user within a given symbol duration:

$$\mathbf{G_4} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \\ -x_4 & -x_3 & x_2 & x_1 \\ x_1^* & x_2^* & x_3^* & x_4^* \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & x_4^* & x_1^* & -x_2^* \\ -x_4^* & -x_3^* & x_2^* & x_1^* \end{bmatrix}. \tag{2}$$

3.3. Adaptation Schemes

STBC has the potential of providing a high diversity gain at the cost of having a relatively low BE due to the fact that the $G4$ STBC structure has a rate of $R = 1/2$. Therefore, in order to maximise the achievable BE, the system was configured to switch between different-BE and different-robustness modes, in order to maximise the effective BE, while maintaining a given target BER performance. A low-BE but high-diversity-gain mode can be activated by the system, when the near-instantaneous SNR is low. By contrast, higher-BE but lower-diversity-gain modes can be activated, while always satisfying the target BER, when the instantaneous SNR is high.

As mentioned in Section 1, in this contribution we consider two different adaptive systems that result in a different throughput, while maintaining the target BER of 10^{-3}. Again, the proposed adaptive systems assume the formation of a cooperative cluster of four users, each having a single transmitter, while communicating with a common BS.

The system parameters of System 1, are listed in Table 1. The system adapts the transmission scheme between the lowest-throughput $G4$-like structure using BPSK at low SNRs, gradually increasing the throughput and switching to the highest-throughput $G4$-like structure in conjunction with the 64-QAM mode activated at high SNRs. The attainable BE varies between 0.364 bits/sec/Hz and 2.18 bits/sec/Hz as follows. Explicitly, at low near-instantaneous SNRs, the low-throughput BPSK mode can be employed and as the near-instantaneous SNR increases, the higher-throughput QPSK mode can be activated. A further increase of the near-instantaneous SNR results in the activation of the $G4$-like cooperative STBC system employing 16-QAM. Finally, the highest-throughput mode is constituted by the $G4$-like cooperative STBC structure employing the high-throughput 64-QAM mode [1]. To elaborate further on how the BE was calculated, let us consider the following calculations carried out for the lowest-throughput and the highest-throughout modes. For the cooperative $G4$-like STBC structure employing BPSK the system transmits 1 bit-per-symbol for each user, which results in a total of 4-bits for the four users. Furthermore, as discussed in Section 3, System 1 requires 11 TSs for the full transmission of the four users' $G4$ STBC frame. Therefore, the BE can be computed as $4/11 = 0.364$bits/sec/Hz. Similarly for the 6 bits-per-symbol 64-QAM scheme the BE can be calculated as $6 \times 4/11 = 2.18$ bits/sec/Hz.

The parameters of System 2 are listed in Table 2. In this system, the V-BLAST ZF receiver is employed all the time, while the number of cooperating users is adapted. A cluster of four users is formed. As the near-instantaneous SNR decreases, the specific user having the lowest near-instantaneous SNR is dropped out from the cooperating cluster and is assigned a different TS by the BS in order to transmit his/her data. As the number of users decreases, the inter-user interference is reduced and thus the system's BER performance tends to improve. When the SNR decreases further, more users are removed from the cooperating cluster, until we are left with four users communicating over four independent TSs. By contrast, when the SNR and

Table 1: System parameters for system 1

No. of users per cluster	4
No. of Rx Antennas	1
Mode 1	$G4$ STBC, BPSK BE= 0.364 bits/sec/Hz
Mode 2	$G4$ STBC, QPSK BE=0.727 bits/sec/Hz
Mode 3	$G4$ STBC, 16-QAM BE=1.454 bits/sec/Hz
Mode 4	$G4$ STBC, 64-QAM BE=2.18 bits/sec/Hz

Table 2: System parameters for system 2

No. of users per cluster	4
No. of Rx Antennas	4
Mode 1	one user BE=2 bits/sec/Hz
Mode 2	Two users BE=4 bits/sec/Hz
Mode 3	Three users BE=6 bits/sec/Hz
Mode 4	Four users BE=8 bits/sec/Hz

SINR increases, the BS may incorporate further users in the cooperating cluster, namely the specific users benefiting from having the channel exhibiting the highest near-instantaneous SNR. Again, this system does not require any exchange of data between the cooperating users, since the users are cooperating to share the system resources such as the carrier frequency and the bandwidth, rather than for the sake of achieving an additional diversity or multiplexing gain. Furthermore, to elaborate in more details on how the BE was calculated in this case, let us consider the following. The system employs QPSK for transmitting 2 bits-per-symbol. When the four users are cooperating in a V-BLAST mode, the system transmits the users' data in a single TS and hence the BE can be computed as $2 \times 4/1 = 8$ bits/sec/Hz. Again, this system does not increase the user BE, although the system BE is increased. In System 2, users are cooperating to share the system resources such as the TSs, rather than for the sake of achieving an additional diversity or multiplexing gain. For example, when no cooperation is incorporated, 4 users transmit their QPSK symbols in four TSs. However, when users are cooperating using System 2, at high SNRs the system accommodates 16 users in four TSs and hence the total data throughput becomes four times the number of users, while maintaining the target BER.

4. RESULTS AND DISCUSSIONS

We consider a system employing a cluster of four users communicating with a common BS, in order to demonstrate the performance improvements achieved by the proposed systems. All simulation parameters of System 1 and System 2 are listed in Tables 1 and 2 which were configured for maintaining a target BER of 10^{-3}.

Figure 2 shows the BER as well as the effective system BE of System 1. The BER curve of the adaptive system, which can be viewed by referring to the y-axis on the left of the figure, is plotted along with those of the individual modes of operation. The BER performance reaches the target BER around SNR$=$ 7 dB and then it never exceeds the target BER for the SNRs considered, while switching between the different transmission modes of Table 1. The y-axis at the right of Figure 2 quantifies the achievable effective BE of System 1. Depending on the channel quality quantified in terms of the channel SNR, the transmitter activates one of the transmission modes outlined in Table 1. The effective throughput of the system varies from 0.364 bits/sec/Hz recorded for the minimum-throughput mode to 2.18 bits/sec/Hz encountered for the highest-throughput mode. Figure 3 portrays the mode selection probability histogram of System 1. It is clear from the figure that as the average SNR increases, the higher-throughput modes are activated more often.

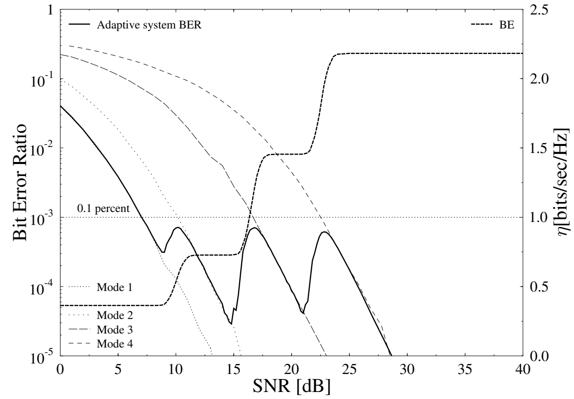

Figure 2: BER and BE performance of System 1 for a target BER of 10^{-3} with perfect IUC.

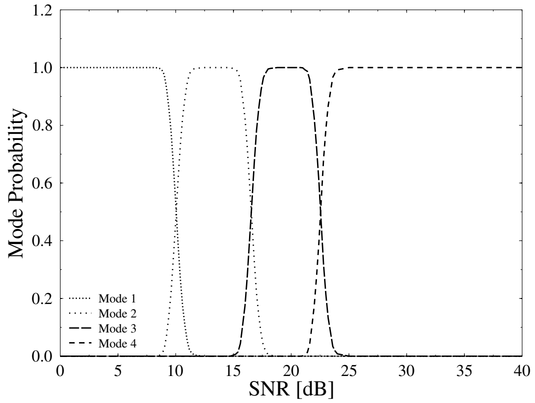

Figure 3: Mode selection probability histogram of System 1 for a target BER of 10^{-3} with perfect IUC.

Figure 4 shows the BER as well as the effective system BE performance of System 2. The BER curve of the adaptive system, which can be viewed by referring to the y-axis on the left of the figure, is plotted along with those of the individual modes of operation. The BER performance reaches the target BER around SNR$=$ 7 dB and then remains below the target BER for all the SNRs considered, while switching between the different transmission modes. The y-axis at the right of Figure 4 quantifies the achievable effective BE of System 2. Depending on the channel quality quantified in terms of the channel SNR, the transmitter activates one of the four transmission modes outlined in Table 2. The effective system throughput varies from 2 BPS for the minimum-throughput mode to 8 BPS for the highest-throughput mode. For example, if we calculate the throughput of Mode 1 characterised in Table 2, supporting a single user employing QPSK, yields 2 BPS. An important point concerning this system is that the individual users' throughput does not vary, while the total cluster's throughput does change. However, as the SNR decreases,

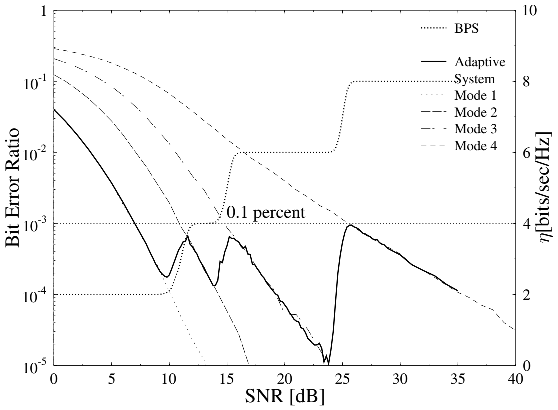

Figure 4: BER and BPS throughput performance of System 2 for a target BER of 10^{-3} with perfect IUC.

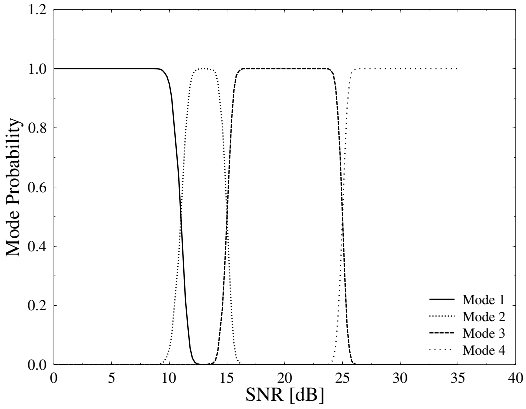

Figure 5: Mode selection probability histogram of System 2 for a target BER of 10^{-3} with perfect IUC.

the BS removes a user from the cooperating cluster, who will communicate with the BS using an independent dedicated channel and thus the overall system requires more resources, such as an additional TDD time slot. Therefore, System 2 maintains the target BER, while increasing the achievable system throughput and minimising the resources required. Figure 5 portrays the mode selection probability of System 2. It is clear from the figure that as the average SNR increases, the higher-throughput modes are activated more often.

5. CONCLUSION

In this paper we proposed two adaptive systems, which amalgamate the advantages of cooperative diversity, distributed STBC as well as V-BLAST, while near-instantaneously adapting the system configuration for the sake of achieving the highest possible throughput, as well as maintaining a given target BER. System 1 benefits from a higher diversity gain with the aid of STBC while varying the BE by adapting the modulation scheme employed. System 1 is capable of maintaining a target BER of 10^{-3} at an SNR as low as 7 dB, while having a BE varying between 0.364 bits/sec/Hz and 2.18 bits/sec/Hz. By contrast, System 2 benefits from the higher multiplexing gain of V-BLAST and thus has an effective BE varying between 2 bits/sec/Hz and 8 bits/sec/Hz. Our future research will consider the mathematical performance analysis of the two proposed systems, in addition to the design of an optimised adaptive scheme, where adaptation will be based on the more reliable channel quality metric of the estimated BER value of the received frames', rather than on the less reliable channel SNR metric.

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